Reprinted from *Agronomy Journal*
Vol. 84, No. 4

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ABSTRACT

Conservation tillage practices, including no-till (NT), reduce soil erosion and increase precipitation storage efficiency, but may decrease available soil N. We conducted studies at two sites to determine the comparative effects of NT and stubble mulch (SM) on the N supplying capacity of Pullman clay loam (fine, mixed, thermic Torrertic Paleustolls) cropped to continuous wheat (*Triticum aestivum* L.) (CW), continuous grain sorghum [*Sorghum bicolor* (L.) Moench] (CS), wheat-sorghum-fallow (WSF), and wheat-fallow (WF) sequences. AT one site, accumulation of NO_3-N in the surface 1.2 m (in kg ha^{-1}) was CW NT - 20, CW SM - 37, CS NT - 28; CS SM - 24, WSF NT - 34, WSF SM - 52, WF NT - 57, and WF SM - 60. Tillage significantly affected N accumulation only on the WSF sequence. Nitrate -N moved deeper into the profile under NT than under SM, indicating that differences in the root zone may have resulted from differential leaching rather than from differential nitrification. Yields under no-till and stubble mulch were similar except on continuous grain sorghum where nitrogen deficiency was encountered and stubble mulch outyielded no-till.

CONSERVATION TILLAGE PRACTICES such as no-till and stubble-mulch have been shown to reduce soil loss by wind and water erosion. Also, under NT, more of the precipitation is stored as soil water, but the supply of available N may be decreased. When under SM, Pullman clay loam and other fine-textured soils of the Southern High Plains have been shown to contain sufficient plant nutrients to produce yields as high as the precipitation allows (Eck and Fanning, 1962; Johnson, et al., 1974). However, under NT, the additional stored soil water increases the yield potential and yields may be limited by the supply of available N.

Unger and Wiese (1979) found that with NT, 35% of the precipitation during the fallow period between winter wheat harvest and grain sorghum planting was stored as soil water. Comparable storage efficiency under SM was 23%, with disk tillage, it was 15%. In a later study under the same cropping system (Unger, 1984), respective storage efficiencies were 45%, 36%, and 28% under NT, SM, and moldboard plowing.

It is generally agreed that more NO_3-N accumulates in cultivated than in NT soil but reasons for the greater accumulation are not always well defined. Rice and Smith (1982) concluded that there was no difference between tillage systems in mineralization rates as long as soil water remained the same. Later, Rice et al. (1986) found that in the first 9 yr of a study comparing corn (*Zea mays* L.) yields under conventional tillage (CT) and NT, yields of unfertilized corn were higher under CT than under NT, but after that, yields were similar under both tillages. They suggested that the lower availability on NT is a transient effect. Lamb et al. (1985) found greater NO_3-N accumulation in moldboard plowed soil than in NT soil during the first several years of tillage but differences narrowed with

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Published in Agron. J. 84:660–668 (1992).

Abbreviations: CW, continuous wheat; NT, no-till; OM, organic matter; OW, oneway plowing; WF, wheat-fallow; and WSF, wheat-sorghum-fallow.

time. They indicated that the NT and SM soils moved toward a new steady state which allows N accumulation to occur at a rate similar to that in plowed soil. McCalla and Russel (1943) measured NO_3-N production and movement where crop residues had been left on the surface by subtillage or incorporated by plowing. They concluded that NO_3-N production was similar under the two tillage methods. The main influence of the surface residues was translocation of NO_3-N downward in the profile. Both Eck and Fanning (1962) and Johnson et al. (1974) reported greater accumulation of NO_3-N in the surface 1.8 m of Pullman clay loam under oneway plowing (OW) than under SM. Johnson et al. also showed greater depletion of soil OM under OW than under SM. Fenster and Peterson (1979) found smaller accumulations of NO_3-N under NT than under plow or subtill. Doran (1980) and Linn and Doran (1984) found significantly more aerobes in the surface 7.5 cm and significantly fewer in the 7.5- to 15-cm layer of untilled compared to tilled soils. Doran believes that mineralization activity in tilled soil peaks immediately after plowing when the soil has been disturbed and aerated. However, during the latter part of the growing season there is greater mineralization in untilled soil due to greater water availability (Fox and Bandel, 1986).

The objective of this study was to determine the comparative effects of NT and SM on N supplying capacity of soil in wheat-sorghum-fallow (WSF), wheat-fallow (WF), continuous wheat (CW), and continuous grain sorghum (CS) cropping sequences.

METHODS AND MATERIALS

Two studies were conducted on Pullman clay loam at the USDA Conservation and Production Research Laboratory, Bushland, TX.

Study 1 was on leveled minibenches (Jones, 1981) on a 1.5% slope (before benching). The site had been dry farmed in CS or WSF sequences for more than 30 yr before the studies were initiated. The 9.1- by 158.5-m benches were constructed across the slope. Leveling had little effect on soil physical and chemical properties (Unger et al., 1990). Treatments included four cropping sequences, CW, CS, WSF, and WF and two tillage treatments, NT and SM. All cropping sequences were evaluated under both tillage treatments. Minibenches were constructed and cropping system and tillage treatments were established in 1982. Treatments were arranged in a randomized block design with three replications. Soil organic matter (OM) concentrations were similar in the three replicates. Average OM concentrations of the 0- to 7.5-, 7.5- to 15- and 15- to 30-cm soil depths were 17.1, 11.4, and 8.7 g kg^{-1}, respectively. Average $NaHCO_3$- extractable P concentrations in the 0- to 7.5-cm soil depths ranged from 12 mg kg^{-1} on Replication 1 (at the bottom of the slope) to 7 mg kg^{-1} on Replication 3 (at the top of the slope). Concentrations in 7.5- to 15- and 15- to 30-cm soil depths were similar on all replications (4 mg kg^{-1} in both soil depths).

The site of the other study (Study 2) consisted of four adjacent fields on a 1.5% slope. Each field was about 600 m long. Widths varied from about 67 to 126 m, giving fields from about 4 to about 7 ha in area. The fields had been dry farmed in WSF sequences using SM tillage for more than 30 yr. The NT treatment was introduced in 1981 when three of the fields, already cropped in sequence so that all conditions (wheat, sorghum, and fallow) occurred each year, were split longitudinally and NT was imposed on one-half of each field. The fourth field was left intact, converted to NT, and cropped to CW. Soil OM and $NaHCO_3$-extractable P concentrations were similar in the four fields. Average OM concentrations of the 0- to 7.5-, 7.5- to 15-, and 15- to 30-cm soil depths were 16.1, 12.5, and 10.0 g kg^{-1}, respectively. Respective $NaHCO_3$- extractable P concentrations were 11, 5, and 6 mg kg^{-1}.

In the WSF sequence, each crop was followed by an approximate 330 d fallow period, allowing two crops in 3 yr. In the WF sequence, wheat was grown in alternate years with approximate 450-d fallow periods between crops.

On NT plots, weeds were controlled with herbicides and the only soil disturbance was that involved in seeding the crops. The weed control program for NT on WSF was as follows: (i) 3.36 kg ha^{-1} atrazine [2-chloro-4-(ethylamino)-6(isopropylamino)-s-triazine] and 0.84 kg ha^{-1} 2-4-D(2,4-dichlorophenoxy) acetic acid applied immediately after wheat harvest, (ii) 0.56 kg ha^{-1} glyphosate [*N* (phosphonomethyl) glycine] + surfactant at sorghum planting, (iii) 1.68 kg ha^{-1} propazine [2-chloro-4,6-bis(isopropylamino)-s-triazine] pre-emergence, (iv) chlorsulfuron (2-chloro-N-[[(4-methoxy-6-methyl-1,3,5-traizin-2-yl)amino]carbonyl] benzenesulfonamide, 23 to 35 g ha^{-1} + surfactant and 2-4-D, 0.56 kg ha^{-1} in February after sorghum harvest, and (v) 0.56 kg ha^{-1} glyphosate + surfactant at wheat planting.

On SM plots, tillage was done with a sweep plow having large (1.8 m) V-shaped blades. First tillages after harvest were about 13 cm deep. Succeeding tillages were at shallower depths, usually just deep enough to control weeds. Three tillage operations were usually required between continuous crops; five were required during fallow periods in the WSF sequences. First post harvest tillage operations were performed as soon as necessary to control weeds. First tillages of grain sorghum plots were in April. Chemical weed control consisted of 1.68 kg ha^{-1} propazine pre-emergence after sorghum planting and 0.56 kg ha^{-1} 2,4-D on wheat in late February.

Soil NO_3-N to 1.8 m was measured at the beginning and end of growing seasons and to 0.3 m at 2- to 3-wk intervals during growing seasons. When dates for deep sampling of the profile did not correspond to planting or harvest dates, data for the 0- to 0.3-m depth from the pertinent planting or harvest date were added to those for the 0.3- to 1.2-m or 0.3- to 1.8-m depth from the nearest deep sampling date. The surface 0.3 m was sampled in three segments; 0.0 to 0.075-, 0.075- to 0.15-, and 0.15- to 0.30 m. Below 0.30 m, sampling was by 0.30 m depth increments. Samples were taken from 5 locations, composited, subsampled, extracted with 0.1 *M* KCl and NO_3-N was determined according to Kamphake et al. (1967). In Study 2, two sets of five-location samples were taken from each plot (field) and averages of the two analytical results are reported. Sampling in this study began in March 1985. In Study 1, single sets of five-location samples were taken from each plot. Sampling for NO_3-N was initiated on the CW and CS sequence plots in April 1986 and on the WSF and WF sequence plots in April 1987.

In deriving NO_3-N data for planting and harvest dates, the most likely chance for error was in planting time data for sorghum. Deep sampling was in April while sorghum planting was in June. Precipitation between deep sampling and planting could have moved NO_3-N from the 0- to 0.3-m depth to deeper in the profile.

Soil water was measured gravimetrically at planting and at harvest of each crop. Measurements were by 0.3-m depth increments to a depth of 1.8 m. Grain and forage yields were determined from hand harvested samples (six each). Sample areas were 9.3 m^2 for grain and 1.52 m^2 for forage.

In Study 1, N fertilizer (56 kg N ha^{-1}) was applied on the CW plots in March 1988 and on CS plots at planting in 1988. At wheat planting in 1988 and at sorghum planting

Table 1. Monthly precipitation at the USDA-ARS Conservation and Production Research Laboratory, Bushland, TX 1985–1989.

Year	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Total
	mm												
1985	22	8	39	27	50	48	51	46	183	65	18	6	563
1986	0	35	14	5	45	126	24	99	48	63	49	18	526
1987	30	36	25	10	134	79	24	101	114	32	13	38	636
1988	9	1	17	53	100	56	54	41	113	7	3	8	462
1989	4	12	6	15	88	136	84	108	77	5	0	14	549
50-yr avg.	12	13	20	27	69	75	63	71	49	42	19	13	473

in 1989, 56 kg N ha^{-1} was applied on all plots, except for two 15 m wide check strips left unfertilized on each plot. All soil samples for NO_3-N analyses were taken from the check strips.

In Study 2, we conducted fertilizer trials with wheat on the areas in wheat in 1985–86 through 1988–89. We studied six treatments: check, 35 kg N ha^{-1}, 70 kg N ha^{-1}, and 70 kg N and 40 kg P ha^{-1} (all fall applied), and 35 and 70 kg N ha^{-1} top dressed in March. The N and P sources were ammonium nitrate and triple superphosphate, respectively. Fall applied fertilizer was applied immediately before planting, after SM treatments had been tilled.

RESULTS AND DISCUSSION

Monthly precipitation data for 1985 through 1989 and 50-yr average precipitation data are given in Table 1. Precipitation was near or above the longtime average during most months of the growing seasons. Climatic conditions were generally favorable for crop production. Yields were much higher than longtime averages. Longtime (1958–1989) average yields at Bushland (under SM) are as follows: CW-860 kg ha^{-1}, CS-1240 kg ha^{-1}, wheat in WSF-1130 kg ha^{-1}, and sorghum in WSF-2300 kg ha^{-1} (Unpublished data, 1990, O. R. Jones).

Although NO_3-N was measured to the 1.8-m depth, data presented in tables and most graphs are limited to the surface 1.2 m of soil. The limitation was made because the soil NO_3-N data indicated that depletion was greatest in that depth and it was often difficult to determine whether there were real changes in NO_3-N levels below that depth. Available soil water was more completely depleted in the 0.9- to 1.2-m depth than at greater depths but the soil water data definitely indicated that both wheat and sorghum removed water from the 1.2- to 1.8-m depths. Removal from the 1.2- to 1.8-m depths was more complete with wheat than with sorghum (Fig. 1).

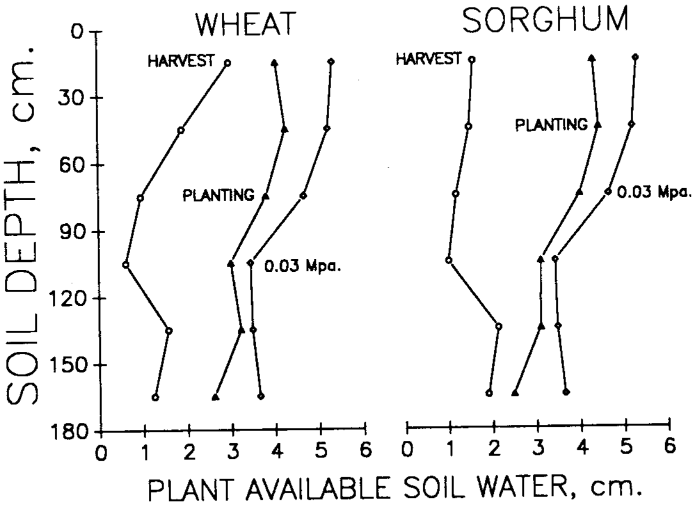

Fig. 1. Plant available soil water (total −1.5 MPa) on wheat-sorghum-fallow sequence at planting and harvest, average no-till and stubble mulch, 1987 through 1989, Study 2.

STUDY 1

Low soil NO_3-N levels and deficiency symptoms prompted N applications in 1988 and 1989. Applied N increased sorghum yields but did not affect wheat yields. Unless indicated otherwise, data presented here are from unfertilized areas in plots.

Grain Yield

Grain yields for 1986 through 1989 are presented in Table 2. The wheat crop was lost to hail in 1989. Data from 1986 through 1988 are available to compare cropping sequences. Wheat yields were higher on WSF and WF than on CW and similar on WSF and WF and

Table 2. Yields of wheat and grain sorghum as affected by tillage methods and cropping sequences, Study 1, 1986 through 1989.

Cropping sequence and year	Wheat NT	Wheat SM	Sorghum NT	Sorghum SM
	kg/ha			
Continuous wheat				
1986	1200a†	1260a		
1987	1510a	1170a		
1988	1240a	1210a		
1989	0	0		
Avg. 1986–1988	1320A	1210A‡		
Continuous sorghum				
1986			3240b	4840a
1987			3620a	4300a
1988			2690a	2600a
1989			2700b	3820a
Avg. 1986–1988			3180B	3910A
Wheat-sorghum-fallow				
1986	1270a	1260a	5330a	5300a
1987	1880a	1990a	5080a	5010a
1988	1260a	1140a	4300a	4340a
1989	0	0	5910a	6280a
Avg 1986–1988	1470A	1460A	4900A	4880A
Wheat-fallow				
1986	1240a	1300a		
1987	1960a	2200a		
1988	1260a	1020a		
Avg 1986–1988	1490A	1510A		

† Means for tillage within crops and years followed by the same lower case letter are not significantly different at the 0.05 level.

‡ Three year average means for tillage within crops followed by the same capital letter are not significantly different at the 0.05 level.

under NT and SM. Grain sorghum yields were higher on WSF than on CS. Continuous sorghum yields were higher on SM than on NT but on WSF, yields were similar under the two tillages. Nitrogen deficiency limited yields of CS in 1988 and 1989 as indicated by N fertilizer responses. In 1988, 56 kg N ha^{-1} increased sorghum yield 54% (from 2.60 to 3.90 Mg ha^{-1}) on SM CS and 61% (from 2.69 to 4.31 Mg ha^{-1}) on NT CS. In 1989, N fertilizer increased yields 18% (from 3.82 to 4.52 Mg ha^{-1}) on SM CS and 96% (from 2.70 to 5.28 Mg ha^{-1}) on NT CS.

Nitrate-Nitrogen Accumulation

Nitrate-N levels in the soil at beginnings of fallow periods and increases during fallow are presented in Table 3.

Under CS NT, accumulation of NO_3-N between harvest and planting ranged from 17 to 42 kg ha^{-1} and averaged 28 kg ha^{-1}. Under SM, the range was from 20 to 29 kg ha^{-1} and averaged 24 kg ha^{-1}. Average accumulation between harvest and deep sampling in April was only 2 kg ha^{-1} (data not shown), thus most of the accumulation occurred between mid-April and mid-to-late June. Although the soil is usually dry at harvest, in both 1986 and 1987, the surface 0.3 m of soil contained adequate water for microbial activity. Thus, mineralization was apparently limited by low soil temperatures.

Under CW, NO_3-N accumulation during the fallow period on NT plots averaged 20 kg ha^{-1} compared with 37 kg ha^{-1} on SM plots (Table 3). Considerably more accumulation occurred in 1987 than in 1988. The difference was probably due to differences in soil water contents during the fallow period. The surface 7.5 cm of soil was dry for much of the fallow period in 1988 (June to mid-August) while it remained wet for most of the fallow period in 1987. The crop was destroyed by hail on 16 May 1989 and was not harvested. Soil water contents were favorable for mineralization throughout the fallow period but less NO_3-N accumulated under NT in 1989 than in 1988. Under SM, however, there was more accumulation in 1989 than in 1988 and almost as much as in 1987. Apparently, some condition other than soil water limited NO_3-N accumulation on NT in 1989.

During the fallow period between wheat and sorghum, accumulation on NT averaged 42 kg ha^{-1} while that on SM averaged 62 kg ha^{-1} (Table 3). Between sorghum and wheat, accumulation on NT averaged 26 kg ha^{-1} and that on SM was 41 kg ha^{-1}. The averages indicate that more N become available in the fallow period after wheat than during the period following sorghum. However, on NT during the 1988 to 1989 fallow periods, NO_3-N accumulation was similar after both crops.

In the wheat-fallow sequence, accumulation was much greater during the 1987 to 1988 than during the 1988 to 1989 fallow period (Table 3). Initial NO_3-N levels were higher in 1988 to 1989 than in 1987 to 1988 indicating the possibility that the easily nitrifiable N was already in that form when the initial samples were taken. Other than this, the reason for differences in NO_3-N accumulation during the two fallow periods is not apparent.

There were significant differences in NO_3-N accumulation due to tillage on CS during the 1986 to 1987 fallow period and on WSF during the sorghum to wheat fallow period (Table 3). Otherwise, differences were not significant. Trends in the data were toward greater accumulation of NO_3-N under SM in the CW and WSF sequences and similar accumulation under the two tillage methods in the CS and WF sequences.

Table 3. Nitrate N in soil (0- to 1.2-m depth) at initiation of fallow and increases during fallow as affected by cropping systems and tillage methods, Study 1.

Cropping sequence and fallow period	No-till		Stubble-mulch	
	Initial	increase	Initial	increase
Continuous sorghum				
18 Nov. 1987–24 June 1987	4	26a†	11	20b
19 Nov. 1987–30 June 1988	8	42a	7	29a
10 Nov. 1988–20 June 1989	3	17a	2	22a
Avg.		28A‡		24A
Continuous wheat				
2 June 1987–8 Oct. 1987	3	32a	13	59a
10 June 1988–19 Oct. 1988	15	18a	37	8a
20 June 1989–12 Oct. 1989	36	9a	39	43a
Avg.		20A		37A
Wheat-sorghum fallow				
Wheat to sorghum				
2 June 1987–30 June 1988	4	53a	8	68a
10 June 1988–20 June 1989	9	31a	11	57a
Avg.		42A		62A
Sorghum to wheat				
19 Nov. 1989–19 Oct. 1988	5	19a	5	40a
10 Nov. 1988–12 Oct. 1989	2	33a	5	42a
Avg.		26B		41A
Wheat-fallow				
23 July 1987–10 Nov. 1988	5	85a	7	118a
29 Aug. 1988–13 Nov. 1989	31	29a	84	2a
Avg.		57A		60A

† Means for tillage within fallow periods followed by the same lower case letters are not significantly different at the 0.05 level.
‡ Overall means for tillage followed by the same capital letter are not significantly different at the 0.05 level.

Soil Nitrate Levels

Soil NO_3-N levels are shown in Fig. 2. The data from the WSF sequence can be used to measure NO_3-N removal between planting and harvest of single crops but cannot be used to measure accumulation between crops because planting-time data shown for the next crop are not from the just previously harvested plots.

Continuous sorghum removed almost all of the NO_3-N accumulated in the 1.2-m soil depth (Fig. 2). Also, NO_3-N decreased in the 1.2- to 1.8-m depth. At planting in 1986, the 1.2- to 1.8-m depths in plots of both tillage treatments contained 84 kg NO_3-N ha^{-1}. After harvest in 1987, most of the NO_3-N on NT plots had been removed from that soil depth. On SM plots, NO_3-N was removed from the 1.2- to 1.8-m depth but not as quickly nor completely as on NT plots. In 1988 and 1989, 22% of the 84 kg ha^{-1} present at planting in 1986 remained in that soil depth. It is unclear whether the crop removed the NO_3-N or whether it was lost by leaching. Figure 3 shows that in the WSF sequence, NO_3-N moved deeper under NT than under SM. However, with continuous cropping, water movement beyond the root zone would not be likely. Still, there were instances when NO_3-N levels decreased in the absence of a growing crop when the soil was near field capacity but there were also de-

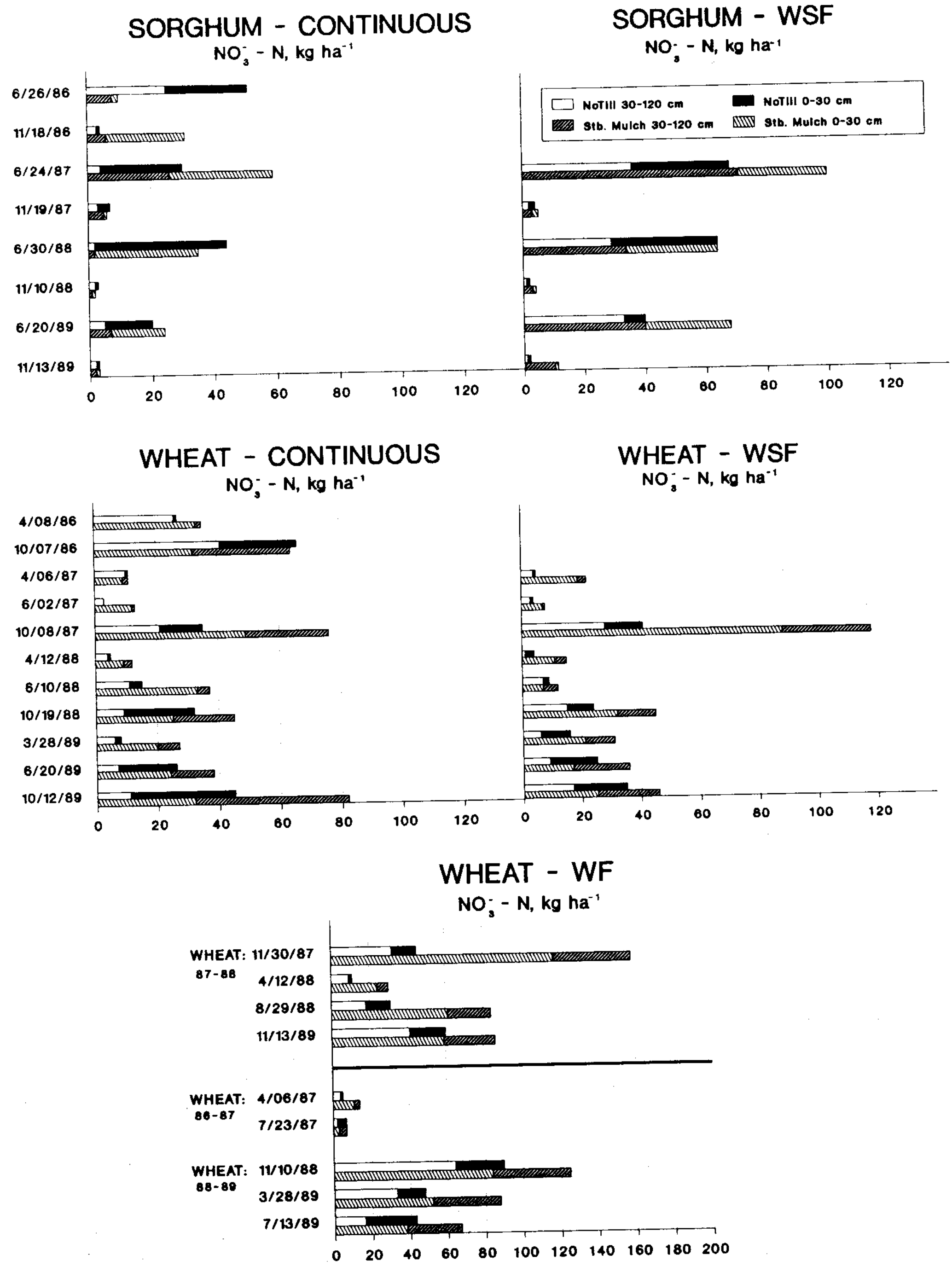

Fig. 2. Tillage [no-till (NT) and stubble-mulch (SM)], cropping system [sorghum, continuous (CS) and in wheat-sorghum-fallow (WSF) sequence, wheat, continuous (CW) and in WSF sequence, and wheat in wheat-fallow (WF) sequence] effects on soil NO_3-N levels. Study 1. Levels in 0.0- to 1.2-m soil depths were higher (p = 0.05) under SM than under NT on CW, WSF, and WF, but differences were not significant on CS.

creases when the soil did not reach field capacity between harvest of one crop and planting of the succeeding one. Our data are not detailed enough to determine whether NO_3-N leaching occurred under continuous sorghum but we consider it possible in the level bordered plots with no runoff allowed. The soil water data show that although most of the water use was from the surface 1.2 m, there was some depletion from the 1.2- to 1.5-m depth with little or no depletion from the 1.5- to 1.8-m depth. This indicates that root activity occurred in the 1.2- to 1.5-m depth but little occurred below that.

With CW, NO_3-N levels in the 0- to 1.2-m soil depth were depleted between planting and harvest but depletion was not as complete as under CS (Fig. 2). The major decrease occurred between planting and the spring sampling. In this period of fall and early spring growth, wheat utilizes N and soil temperatures are too cold for appreciable N mineralization. Apparently, between early spring and harvest, current mineralization furnished the N for wheat growth.

In April 1986, the 1.2- to 1.8-m depths on the CW NT and SM plots contained 81 and 86 kg of NO_3-N ha^{-1}, respectively. By June 1987, the NO_3-N level in that depth on NT was reduced to 33 kg ha^{-1}. On SM plots, the NO_3-N level remained substantially unchanged. The soil water data showed that neither the NT nor the SM profiles were wetted enough for leaching to have occurred.

As with grain sorghum, there was some water depletion from the 1.2- to 1.5-m soil depth but little, if any, from the 1.5- to 1.8-m depth. However, the 1.2- to 1.5- and 1.5- to 1.8-m soil depths on CW plots were always drier than equivalent depths on CS plots, indicating that wheat dried the soil at those depths more than sorghum did.

In the WSF sequence, NO_3-N levels at sorghum planting were higher than those on the CS plots but at harvest, NO_3-N was almost completely exhausted on both crop sequences (Fig. 2). At wheat planting, however, NO_3-N levels usually were higher on CW plots than on those of the WSF sequence. The lower levels on WSF plots at wheat planting resulted from the near complete exhaustion of NO_3-N at sorghum harvest. There was not enough N mineralized during the fallow period to increase NO_3-N to levels on CW plots.

After we measured greater downward movement of NO_3-N on NT than on SM fields in Study 2, we determined NO_3-N to 3.6-m depths on WSF plots in this study. Nitrate-N had moved deeper on NT plots than on SM plots (Fig. 3). We did not sample these plots deep enough to measure the total accumulation of NO_3-N below the root zone but the data show that there was deeper movement under NT than under SM.

On the WF sequence, there were 450-d fallow periods between crops. This allowed comparatively large accumulations of NO_3-N (Fig. 2) and at the same time, increased the probability of NO_3-N leaching. At planting in 1987, 1988, and 1989, the surface 1.2 m of soil on NT plots contained 45, 120, and 60 kg NO_3-N ha^{-1}, respectively. Comparative levels on SM plots were 158, 125, and 86 kg NO_3-N. These data indicate more NO_3-N present on SM plots but not necessarily more mineralization since more leaching may have occurred on NT plots.

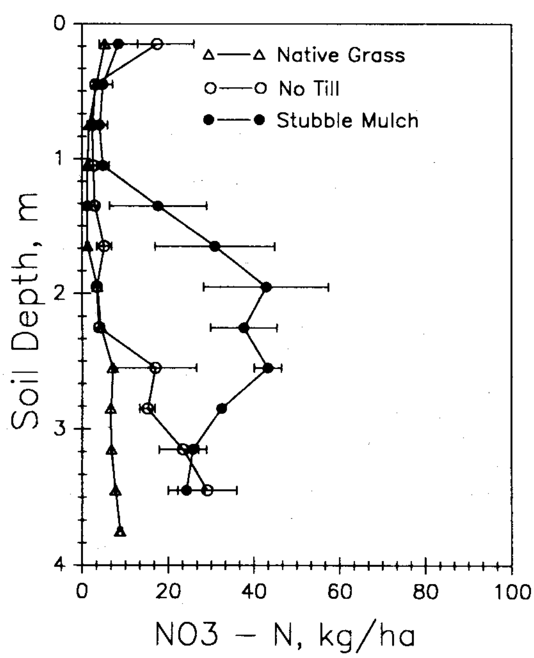

Fig. 3. Effects of cropping and tillage on depth profiles of soil NO_3-N. Wheat-sorghum-fallow sequence and nearby virgin sod. March 1990. Study 1. The horizontal error bars for the measured values represent ± one standard deviation.

Root zone (0–1.2 m) NO_3-N levels were similar under NT and SM on CS, however, they were usually higher under SM on CW. Also, they were almost always higher under SM on WSF and WF too. Differences under CW indicate more mineralization on SM but NO_3-N concentrations in the surface 0.3 m of soil were usually similar under NT and SM. Possibly, mineralization is similar under the two tillage methods and differences in root zone NO_3-N levels result from differential leaching. As shown in Fig. 3, the NO_3-N front was deeper under NT than under SM. In this study, the average (1987–1990) NO_3-N levels in the 1.2- to 1.8-m depths of NT and SM plots in the WSF sequence were 17 and 60 kg ha^{-1}, respectively and levels under the two tillage treatments on the WF plots were 40 and 86 kg ha^{-1}. Nitrogen mineralization may be higher under SM as others have found but differential leaching definitely accentuated differences in root zone NO_3-N levels in this study.

STUDY 2

Grain Yield

Grain yields for 1985 through 1989 are presented in Table 4. The wheat crop was hailed out on 16 May 1989, thus there are no wheat yields for 1989. Data

Table 4. Yields of Wheat and Grain Sorghum as Affected by Tillage Methods and Cropping Sequences, Study 2, 1985 through 1989.

Field or field pair†	Wheat		Sorghum	
	No-till	Stubble-mulch	No-till	Stubble-mulch
	kg ha^{-1}			
Cont. Wheat				
1985	1450			
1986	1160			
1987	1560			
1988	1700			
1989	—			
Total	5860			
Avg. 1986–1988	1470			
‡WSF 1				
1985	—	—	—	—
1986	2030	1950	—	—
1987	—	—	5280	5100
1988	—	—	—	—
1989	—	—	—	—
Total	2030	1950	5280	5100
WSF 2				
1985	—	—	3360	2160
1986	—	—	—	—
1987	2350	2500	—	—
1988	—	—	3110	3100
1989	—	—	—	—
Total	2350	2500	6470	5260
WSF 3				
1985	1410	1080	—	—
1986	—	—	5610	5370
1987	—	—	—	—
1988	1810	1650	—	—
1989	—	—	4260	4560
Total	3220	2720	9870	9930
Avg. 1986–1988	2060	2040	4660	4520

† Field pairs consist of two adjacent fields, one no-tilled and one stubble mulched. Each pair in wheat-sorghum-fallow sequence so that wheat, sorghum, and fallow are present each year.
‡ WSF = wheat-sorghum-fallow sequence.

are given for all years to show total yields but since only one cycle of the WSF sequence was completed, data from 1986, 1987, and 1988 are available to compare cropping sequences. The average annual yield of CW was 1.47 Mg ha^{-1}. Grain yields were similar under NT and SM. Average yields of wheat in the WSF system were 2.06 and 2.04 Mg ha^{-1} under NT and SM, respectively. Respective average yields of grain sorghum were 4.66 and 4.52 Mg ha^{-1}.

Nitrate-Nitrogen Accumulation

Nitrate-N levels in the soil at beginnings of fallow periods and increases during fallow are presented in Table 5.

The amount of NO_3-N accumulated during fallow on CW NT treatment plots ranged from 12 kg ha^{-1} in 1989 to 38 kg ha^{-1} in 1986 and averaged 26 kg ha^{-1} for the four fallow periods (Table 5). Considerably more NO_3-N accumulated in 1986 and 1987 than in 1988 and 1989. In 1988, the surface 7.5 cm of the soil was dry for much of the time from the harvest-time sampling until mid-September while in 1986 and 1987, soil water conditions were more favorable for mineralization (Table 1). In 1989, the crop was destroyed by hail on 16 May and the harvest-time sampling was delayed until 11 July. Soil water and temperature conditions were favorable for mineralization between mid-May and mid-July. The initial NO_3-N level was comparatively high, indicating that much of the easily nitrifiable N may have been nitrified before the harvest-time samples were taken.

Table 5. Nitrate N in soil (0- to 1.2-m depth) at initiation of fallow and increases during fallow as affected by cropping systems and tillage methods, Study 2.

Cropping system and time period	Field	No-till		Stubble mulch	
		Initial	Increase	Initial	Increase
		kg ha^{-1}			
Continuous Wheat					
17 July 1986–7 Oct. 1986		62	35		
15 July 1987–8 Oct. 1987		22	38		
19 July 1988–28 Sept. 1988		10	19		
11 July 1989–21 Sept. 1989		56	12		
Avg		38	26		
Wheat-sorghum-fallow					
Wheat to sorghum					
2 July 1986–24 June 1987	WSF 1	53	54	136	40
7 July 1987–29 June 1988	WSF 2	16	46	61	69
19 July 1988–19 June 1989	WSF 3	8	51	13	46
Avg		26	50	70	52
Sorghum to wheat					
25 Nov. 1985–7 Oct. 1986	WSF 2	42	92	74	139
18 Nov. 1986–8 Oct. 1987	WSF 3	27	35	55	12
19 Nov. 1987–28 Sept. 1988	WSF 1	7	73	26	79
7 Nov. 1988–21 Sept. 1989	WSF 2	3	76	51	37
Avg		20	69	52	67

In the WSF sequence, during the fallow period between wheat and sorghum, NO_3-N accumulation averaged 51 kg ha^{-1}. During the fallow period between sorghum and wheat, accumulation averaged 68 kg ha^{-1}. In Study 1, during the same fallow periods, NO_3-N accumulation between wheat and sorghum was greater than that between sorghum and wheat. With opposite results in the two studies, we have not determined the fallow period in which more NO_3-N is likely to accumulate. Any difference is probably due to kind and quantity of residue present since both fallow periods occur during time periods when temperature and soil water conditions are favorable for N mineralization.

Although variations occurred among years, average NO_3-N accumulations were similar under the two methods of tillage. In Study 1, however, there were trends (and some significant difference) toward more NO_3-N accumulation under SM than under NT. If these soils move toward the new steady state described by Lamb et al. (1985), the equilibrium may have been reached in Study 2 but probably not in Study 1. However, the different responses to residual N fertilizer between NT and SM in Study 2 indicate that SM soil supplied more N to plants than NT soil.

Soil Nitrate-Nitrogen Levels

Nitrate N levels in the surface 1.2-m of soil are presented for the three sets of WSF plots and the CW treatment (Fig. 4). The graphs show an overall decrease in NO_3-N over the study period with increases during fallow periods and decreases during cropping. Decreases were more drastic with sorghum than with wheat due to the higher yields and accompanying uptake by sorghum. The overall decrease over the period indicates that more N was removed than was mineralized during this period of high yields. Nitrogen levels were reduced to a level that N deficiency was observed on NT sorghum plots in 1989. Stubble mulch plots almost always contained more NO_3-N than NT plots. The difference was statistically significant (0.05 level) on two of the three sets of plots. Lack of significance on the third set probably resulted from the NO_3-N levels being very low under both tillage treatments.

Nitrate-N levels became low on the CW plots and N deficiency symptoms were apparent on the 1988 crop but N applications did not affect yields. Apparently, the low N levels were sufficient to produce yields as high as the limited water supply allowed.

Nitrate-Nitrogen Losses

At the initiation of Study 2, NO_3-N levels in the soil were high. They were especially high in the 1.2- to 1.8-m depth where the average NO_3-N level was 126 kg ha^{-1}. Between March 1985 and November 1989, the WSF NT plots lost an average of 89 kg NO_3-N ha^{-1} and the CW NT plots lost 75 kg NO_3-N ha^{-1} from that depth. Like depths on the SM plots lost only 9 kg NO_3-N ha^{-1}. The yield data did not indicate that the N was removed by crops. In February 1990, we sampled to 3.6 m on the CW plots and the WSF plots in fallow after wheat. We found that part of the NO_3-N lost from the 1.2- to 1.8-m depth had moved to the 1.8- to 3.6-m depth but that levels were still rather high at the 3.6-m depth, especially in the NT soil profile. We then sampled WSF plots planted to wheat after fallow to 6 m and found NO_3-N distributed as shown in Fig. 5. The NT and SM treatment plots contained 511 and 470 kg NO_3-N in their 6-m profiles. The NO_3-N had leached deeper on NT than on SM.

Most of the loss of NO_3-N from the 1.2- to 1.8-m depth on the CW NT treatment plots occurred between harvest in 1987 and 14 April 1988. Although it does not seem likely that the NO_3-N was removed by leach-

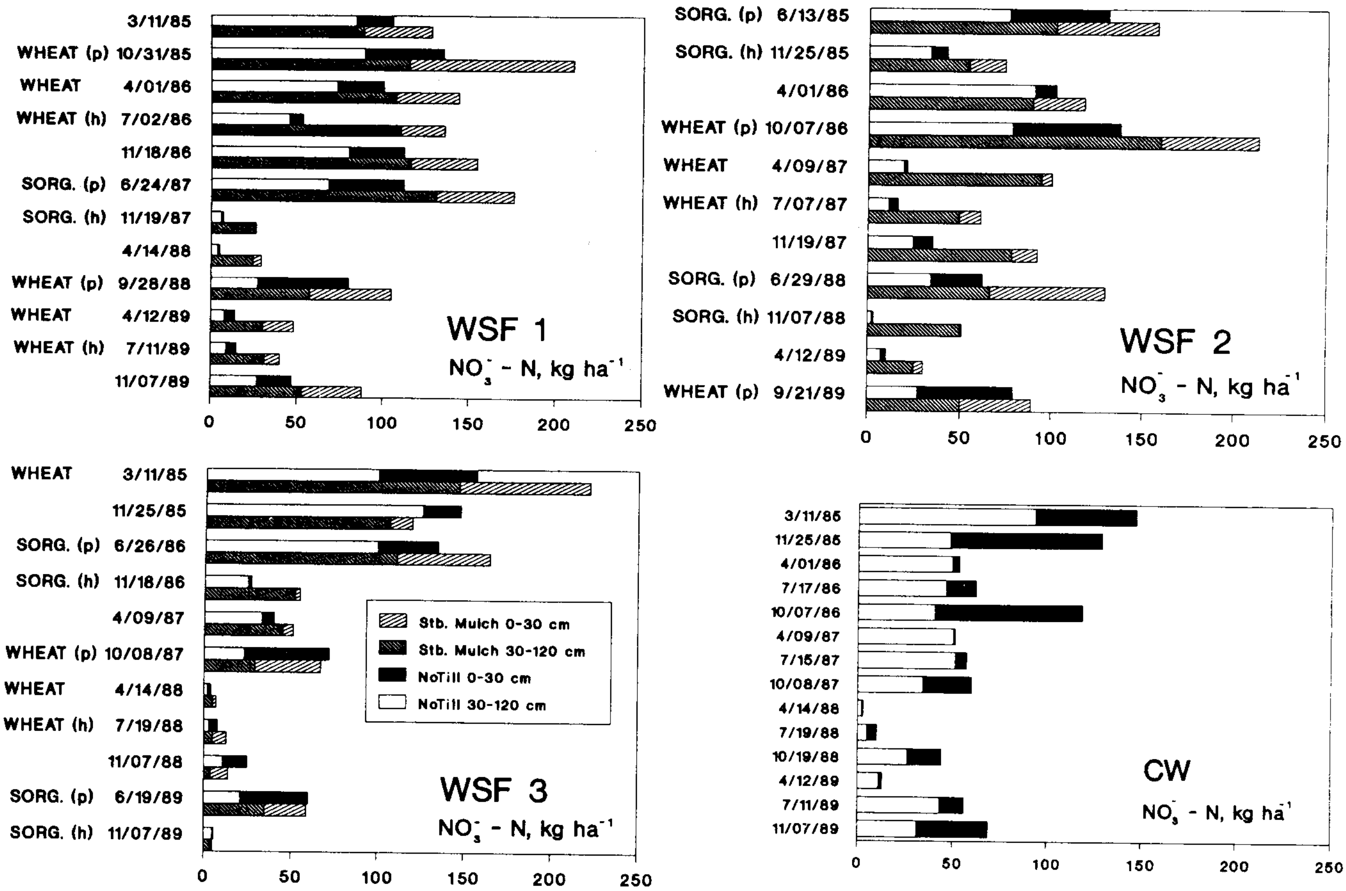

Fig. 4. Tillage [no-till (NT) and stubble mulch (SM)], cropping system [continuous wheat (CW) and wheat-sorghum-fallow (WSF) sequence] and crop removal (with time) effects on soil NO_3-N levels, Study 2. WSF 1, 2, and 3 were three adjacent fields, cropped in sequence so that all conditions (wheat, sorghum, and fallow) occurred each year. NO_3-N levels in 0.0– to 1.2–m soil depths were higher (p = 0.05) under SM than under NT on WSF 1 and WSF 2 but differences were not significant on WSF 3.

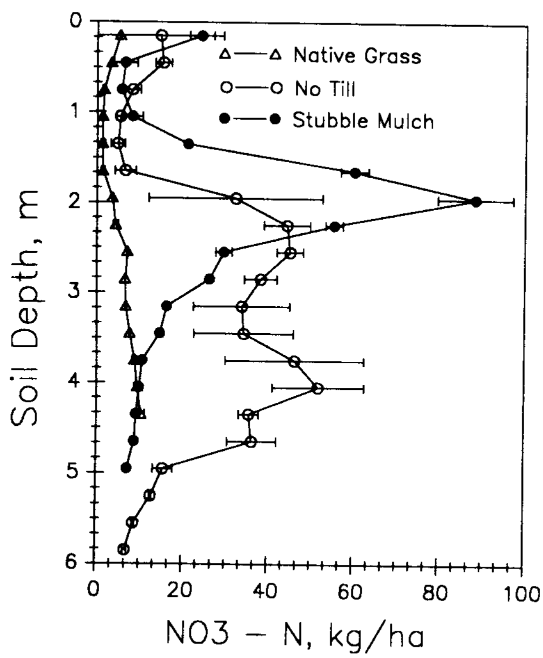

Fig. 5. Effects of cropping and tillage on depth profiles of soil NO_3-N. Wheat-sorghum-fallow field 2 (WSF 2) and nearby virgin sod. February 1990. Study 2. The horizontal error bars for the measured values represent ± one standard deviation.

ing, that seems the most probable way. Soil water data show that 45% of the 247 mm of precipitation received between harvest and planting was stored in the 1.8-m soil profile. At planting, water content in the profile was 60 mm below field capacity and no 0.3-m layer was at field capacity. An additional 112 mm of precipitation occurred between planting and 14 April but with the growing crop, leaching would not be expected. Conditions for denitrification probably would not occur in that portion of the soil profile.

Fertilizer Responses

There were no significant differences in wheat yields due to fertilizer treatments in 1986, 1987, or 1988 and the crop was destroyed by hail in 1989. There were visual differences on the CW plots during the rapid growth stage in Spring 1988 but soil water was exhausted before the crop matured. There were no visual differences due to fertilizer treatments on the WSF treatments in any year. Apparently, the soil supplied sufficient plant nutrients for as high yields as the water supply allowed.

In 1989, grain sorghum was harvested on the WSF plots of the wheat fertility trial harvested in 1988. No additional fertilizer was applied for the sorghum. There was a significant response to residual N on NT (O N, 4.46 Mg ha^{-1}; 70 N Spring, 7.02 Mg ha^{-1}) and a trend toward higher yields with residual N on the SM plots (0 N, 4.96 Mg ha^{-1}; 70 N Spring, 6.23 Mg ha^{-1}).

CONCLUSIONS

Under CS, fallow-period NO_3-N accumulations in the 0- to 1.2-m soil depth were similar under NT and SM while under CW, there was a trend toward higher NO_3-N accumulation under SM. In Study 1, SM plots accumulated significantly more NO_3-N than NT plots during the fallow period between sorghum and wheat and there was also a trend toward more NO_3-N accumulation on SM plots during the fallow period between wheat and sorghum. In Study 2, NT and SM plots accumulated similar amounts of NO_3-N. Under WF, NO_3-N accumulation was similar in NT and SM treatment plots.

Deeper accumulation NO_3-N below the root zone on NT compared to SM indicated greater leaching under NT. Differential leaching rather than differential N mineralization may be responsible for differences in NO_3-N accumulation in the root zone.

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